Minnich et al.: Tree Species Distributions
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pp. 186–202

TREE SPECIES DISTRIBUTIONS IN NORTHERN BAJA CALIFORNIA INTERPRETED FROM GOOGLE EARTH IMAGERY

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ABSTRACT

In Google Earth, the ability to digitize boundary data directly on imagery allows for the creation of high-precision maps. Imagery can also be sampled for population characteristics over time. Using Google Earth, this study develops a new high-resolution baseline of tree distributions in Mediterranean climates of northern Baja California, Mexico, using imagery obtained between 2002 and 2008. The maps presented here have greater precision than previous efforts and include range expansions for several species.

Key words: Arizona cypress forest, Baja California, closed-cone conifer forest, geographic information systems, Google Earth, imagery interpretation, mixed-conifer forest, pinyon-juniper woodland, riparian forest, species ranges, subalpine forest.

INTRODUCTION

In biogeography and ecology, it is vital to develop baseline data to evaluate the dynamics of ecosystems over long time and broad spatial scales. Little consensus has emerged from ecological studies because hypothesis testing has a limited empirical foundation and scale (Jackson et al. 2001). To enlarge spatial and temporal scales, it is vital to "buy time" by analyzing ecological problems at broad scales from time-series aerial photographs, space imagery, and historical field databases. Such analyses require the development and assessment of high-resolution maps of plant assemblages and their properties.

In Google Earth,™ the ability to digitize boundary data directly on imagery allows for the creation of high-precision maps, and imagery can also be sampled for population characteristics over time. The resolution of Digital Globe and other imagery on Google Earth permits the identification of shrub and tree species. In addition, the historical aerial photography feature of Google Earth allows for the study of the fate of forest ecosystems over time. The achievement of Google Earth is the ability to map geographic data directly onto imagery. This eliminates several steps (and costs) in the production of geographic data: (1) original analysis of imagery independently of base maps; (2) transfer of data from imagery to base maps; (3) digitizing of base map data into a geographic information system; and (4) reduction of data loss in the transfer processes. Google Earth also permits the viewer to evaluate areas that have not been visited by the trained eyes of biologists (Minnich et al. 2011).

Using Google Earth, this study develops a new high-resolution baseline of tree distributions in Mediterranean climates of northern Baja California. The Mexican State of Baja California has been a magnet for botanists since the late 19th century. The region has been well collected for nearly a century (Goldman 1916; Nelson 1921; Wiggins 1980; Cody and Case 1983; Case et al. 2002). But paved highways are few, and the mountains are only locally traversed by dirt roads. Extensive areas have never been examined with a scientific eye. Early maps of Baja California give general geographic ranges of tree species that were based on botanical collections, field views, and deductions from species elevational ranges and other criteria (Critchfield and Little 1966; Little 1971, 1976; Griffin and Critchfield 1972). Using Google Earth, this study develops a new high-resolution baseline of tree distributions in Mediterranean climates of northern Baja California.

REGIONAL SETTING

Northern Baja California lies in the Peninsular Range Province that includes a series of discontinuous ranges running parallel to the Gulf of California. In the northern peninsula, the Sierra

Juárez (SJZ) and Sierra San Pedro Mártir (SSPM) form the crest of the Peninsular Range. The SJZ is a tilted, westward-dipping fault block with summit plateaus and summits to 1800 m. It is flanked on the W by a series of ranges that extend from Tijuana to Ensenada, termed here the "coast range," and eastward along the Agua Blanca fault to Paso San Matías, called the "transverse range," with summits increasing from 1200 m in the N to 1600 m in the S. The transverse range merges with volcanic tablelands of the southern SJZ. South of Paso San Matías, the SSPM is an uplifted broad plateau ranging from 2500 m in the N to 1800 m in the S that is bounded by fault escarpments facing the Pacific and the Gulf of California. Summits on the northern plateau rise to 2600 m on the western ridge (Corona Arriba) and to 2700–2900 m along the eastern ridge that hosts the National Observatory. Picacho del Diablo, which arises within the eastern escarpment, has a summit altitude of 3100 m. The region consists of prebatholithic metasedimentary rocks toward the coast (Alisos formation) and exposed plutonic bedrock of the Cretaceous Peninsular Range batholith in the interior, with local metamorphic pendents and Tertiary volcanic caprock (Gastil et al. 1975).

Baja California lies at the southern end of the Mediterranean-climate (winter rain/summer drought) region of the North American Pacific coast. Orographic lift of frontal storm air masses from the North Pacific by the Peninsular Ranges results in mean annual precipitation amounts increasing to 25–40 cm along the coast range, 40–50 cm on the coastal flanks of the SJZ, and 50–70 cm in the Sierra San Pedro Mártir (Minnich and Franco-Vizcaíno 1998). Precipitation decreases to <10 cm in the Sonoran Desert. Mean winter temperatures range from 10ºC in the coast and deserts to 0ºC in the mountains >2000 m. In summer, mean temperatures along the coast are 18ºC due to the influence of the Pacific marine layer, but increase to 25ºC in the interior valleys, and 30ºC in the deserts, then decrease with altitude to 18ºC in the mountains >2000 m (Minnich 2007).

Mediterranean chaparral, oak woodland, and mountain conifer forest extend from southern California to the Sierra San Pedro Mártir (Minnich and Franco-Vizcaíno 1998). Hillslopes from below 1500 to 2000 m are covered with extensive carpets of chaparral with patches of serotinous conifer forests and pinyon woodland. Lower coastal slopes, basins, and canyons contain oaks and riparian gallery forest along watercourses. Above 1500–2000 m, chaparral gives place to mixed conifer forest. Subalpine forest grows near meadows and on the highest summits of the SSPM. Desert-facing drainages are covered with pinyon-juniper woodland and Arizona cypress forest.

METHODS

Google Earth is an analytical tool for spatial analysis of geographic features (Minnich et al. 2011). Vegetation was inventoried using high-resolution Digital Globe and other imagery of Google Earth. Imagery was examined by graduated scaling, the zoom function allowing for the observation of broad scale patterns of vegetation and terrain at small scales, and near-ground (large scale) identification of vegetation features. A measuring function can be used for distance and slope, based on coordinate and elevation data. Species ranges were electronically delimited in files using the digitizer function of Google Earth.

The maps produced for this study were developed by digitizing directly onto Google Earth imagery. Tree species were identified based on morphology, stature, and color (Table 1) and supported by data from botanical collections mostly at the San Diego Natural History Museum. The authors have collected information on the vegetation in nearly all of the region since the 1980s, and maps have been produced in conjunction with fire-history studies in chaparral (Minnich and Chou 1997), mixed conifer forest (Minnich et al. 2000), and spatial ordination of chaparral and forest zonation with elevation and terrain (Minnich 2001). In the Google Earth analysis, species were mapped one at a time, rather than by simultaneously mapping multiple species regionally. This protocol allows for the focus on morphological properties that permit diagnostic identification of each species. In addition, the region is observed repeatedly, which encourages the recognition of "surprises" and omissions. Identifications are deduced based on the finite number of species in each of the life form classes known from northern Baja California. The "time series aerial photo feature" was used to establish the best imagery for each species. Coverages with burned vegetation were avoided.

Google Earth imagery was scanned comprehensively in an "X-Y" format, including extensive areas where forests are not found. Imagery was examined at the smallest possible scale within the resolution of trees to efficiently scan maximum area, ca. 1500 m above ground (cf. Minnich et al. 2011). When a population was suspected or encountered, Google Earth was scaled to 600 m above ground to confirm identification. Closer inspection was not possible due to pixelation of

Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
pp. 186–202

imagery. Although Google Earth imagery is monoscopic, the tilt feature in Google Earth was used for three-dimensional viewing of terrain and rock substrate properties of individual populations. Resolution does not permit the use of the tilt function for 3-D viewing of trees. Imagery was examined looking "S" (S to top) against the light, especially in coverages with large sun angles (winter). This allows the observation of tree morphology independently of shadows, i.e., to avoid repetitive illusion between crowns and shadows. A "N view" (N to top) was taken to examine tree shadow morphology. Only forests sufficiently mature to be identified on imagery were delimited. Hence, immature stands may be present beyond the ranges indicated, particularly in assemblages subject to stand-replacement fires. However, the use of imagery from different periods will show changing distributions of species. Tree ranges were defined at a 10% cover threshold consistent with previous work (Minnich 1987) and definitions of vegetation maps of the California VTM survey (summarized in Keeler-Wolf 2007).

Table 1. Morphological properties of tree species as viewed on Google Earth.

<u>Coniferous trees <5–15 m tall</u>

Cupressus forbesii (Jeps.) D.P.Little and *C. guadalupensis* S.Watson. Trees <10 m, crown perimeters frequently spired at apex, perimeters round, diameters <5 m, crown bases contiguous with shrub understory, foliage dark green to blue-green. Trees mixed aged, i.e., mixed stature on rock outcrops.

Pinus attenuata Lemmon. Trees 5–15 m tall, crown apices rounded, perimeters rounded to slightly ragged, diameters ca. 5 m, crown bases contiguous with understory shrub layer, foliage distinctly bright green to yellow-green. Crowns extend to ground or shrub understory. Stems as tall as 15 m, strongly even aged with stature increasing with time-since-fire. Much larger than *Cupressus forbesii* where the two species grow together.

Pinus muricata D.Don and *P. radiata* D.Don. Trees to 15 m tall, rarely 20 m, crowns narrow <5 m diameter, apices rounded, crown bases contiguous with understory shrub layer, foliage distinctly dark reddish-green. Tree stature locally even aged, tree stature increasing with time-since-fire, but mixed aged on rock outcrops.

<u>Coniferous trees 15–25 m tall</u>

Pinus coulteri D.Don. Trees to 25 m, spired crown apices, with distinctively broad, stellate perimeters, crown bases contiguous with shrub understory. Crown diameters to 15 m, foliage blue-green. Tree stature even aged and increasing with time-since-fire. Stands mixed aged on rock outcrops, often with raised crown bases.

Pinus quadrifolia Sudw. Trees to 15 m, crowns forming cones at apex, diameters 3–7 m, perimeters mostly entire, crown bases contiguous with ground, foliage blue-green. Stands always mixed aged but with average tree stature increasing with time-since-fire.

Pinus monophylla Torr. & Frém. Trees to 20 m, crown apices and perimeters ragged, diameters 3–7 m, crown bases contiguous with ground, foliage blue-green. Stands strongly mixed aged but with average stature increasing with time-since-fire. Stand stature generally taller than *P. quadrifolia*.

Cupressus arizonica var. *stephensonii* (C.B.Wolf) Little. Trees to 10 m but rarely 20 m along watercourses, dense crowns with diameters as large as tree stature, perimeters rounded, crown bases contiguous with understory, crown summits occasionally spired in young trees. Foliage very dense, and distinctly blue-green to turquoise.

Cupressus arizonica var. *montana* (Wiggins) Little. Trees to 25 m, crown diameters frequently comparable to tree stature, perimeters rounded to slightly ragged with diameters to 15 m, crown bases contiguous to 5 m above ground. Apices spired in young trees. Foliage very dense and distinctly blue-green to turquoise.

<u>Coniferous trees 25–45 m tall</u>

Pinus jeffreyi Grev. & Balf. Trees 25–35 m tall, rarely to 45 m in basins. Crown apices spired in young trees, rounded to flat in old trees, wind-flagged on exposed ridgelines, perimeters rounded to stellate, diameters 5–10 m, crown bases 5–10 m above ground. Foliage green to slightly blue-green. Stands universally mixed aged with local tree stature unrelated to time-since-fire, except post-fire cohorts increasing in size in stand-replacement burns to <50 years in age.

Pinus lambertiana Douglas. Trees 25–40 m tall, crown bases 5–10 m above ground, distinctive stellate pendulous branches. Crown diameters 5–10 m, occasionally to 15 m, apices spired in young trees, rounded to flat in old trees, foliage green to blue-green. Stands universally mixed aged with local average tree stature unrelated to time-since-fire.

Abies concolor (Gordon & Glend.) Hildebr. Trees 25–35 m tall, perimeters rounded and entire, with crown diameters <10 m, crown bases 0–10 m above ground, foliage distinctly blue. Crown apices spired and symmetrical in young trees, rounded to flat in old trees. Trees shorter than *Pinus jeffreyi* and *Pinus lambertiana* in mixed stands. Stands mixed aged, average tree stature unrelated to time-since-fire, except in stand-replacement burns <50 years old.

Calocedrus decurrens (Torr.) Florin. Trees 20–45 m tall, crown bases 5–10 m above ground, conical to irregular crown perimeters with diameters of 5–15 m, foliage distinctly bright yellow-green.

Pinus contorta Loudon. Tree stature to 30 m, crowns distinctly narrow and round, <5 m diameter, crown bases <3 m above ground, foliage distinctly brownish green.

<u>Evergreen hardwood trees 15–25 tall</u>

Quercus agrifolia Née. Trees 15–25 m tall, with spreading, multilobed, undulating crown summits, irregular to ragged perimeters, with diameters to 20 m. Foliage dark olive green.

Quercus engelmannii Greene. Trees 10–20 m, crown summits spreading, undulating, perimeters rounded with diameters to 10 m, partly deciduous in winter, foliage blue-green.
Quercus peninsularis Trel. Trees <20 m, with spherical crowns with embedded horizontal branch layering, rounded perimeters to 15 m diameter, partly deciduous in winter. Foliage bright green in growing season.
Quercus chrysolepis Liebm. Shrubby trees <15 m, but to 25 m with raised crowns along streams. Distinctly spherical, dense crowns with entire perimeters. Crown diameters frequently greater than tree stature. Foliage dark olive green.

Deciduous hardwood trees, 15-40 m tall
Populus tremuloides Michx. Trees mostly <15 m tall, but locally to 25 m. Narrow spired crowns, with round perimeters <5 m. Distinct tree clustering due to cloning, foliage brilliant green in summer, yellow in autumn. Trees entirely deciduous in winter.
Populus fremontii S.Watson. Trees 20–40 m tall with spreading rounded to lobed crowns to 15 m diameter. Foliage bright green in summer, yellow in autumn. Mostly deciduous in winter.
Platanus racemosa Nutt. Trees 20–40 m tall, with irregular to stellate crowns to 15 m diameter. Foliage dark brilliant green in summer, yellow-orange in fall, with sparse, dry leaves persisting in winter.

Online Google imagery was consulted between August 2007 and February 2008. The database digitized on Google Earth consists of files of each species formatted in the keyhole markup language (kml). The file format was subsequently converted to a feature classes "shape" file for spatial analysis and map preparation using ESRI ArcGIS Desktop 9.1 operating under an ArcInfo License (Environmental Systems Research Institute, Inc. 2005). Place names of localities are given below in decimal coordinates in Table 2.

Table 2. Place names and coordinates (decimal degrees).

Place name	Latitude (ºN)	Longitude (ºW)
Arroyo El Ciprés	31.44	115.81
Arroyo El Berrendo	30.54	115.16
Arroyo El Cajon	30.85	115.27
Arroyo El Tule	31.87	115.95
Arroyo Hediondo	31.26	116.31
Arroyo La Grulla	31.63	116.40
Arroyo Las Palomas	31.74	115.89
Arroyo San Rafael	31.11	115.76
Arroyo San Simón	30.53	115.73
Arroyo Santa Eulalia	30.73	115.32
Arroyo Santo Domingo	30.80	115.81
Cañon El Rincón	31.70	115.74
Cañon Nueva York	30.65	115.74
Cañon San Isidro	32.29	116.33
Cerro "2040"	30.57	115.35
Cerro "2100"	30.72	115.37
Cerro Botella Azul	30.97	115.95
Cerro Chato	30.58	115.23
Cerro El Golpe	32.11	116.66
Cerro La Noche	31.41	115.54
Cerro Leon	31.56	116.06
Cerro Los Pinos	31.74	116.33
Cerro Miracielo	31.83	116.52
Cerro San Antonio	31.77	116.32
Cerro San Javier	32.50	116.49
Cerro San Matías	31.25	115.54
Cerro Venado Blanco	31.09	115.49
Corona Arriba	31.02	115.56
El Álamo	31.59	116.05
El Morro	30.41	115.40
El Pinal	32.19	116.29
El Topo	32.25	115.97
Ensenada	31.86	116.60
Eréndira	31.26	116.28
La Encantada	30.90	115.41
La Grulla	30.89	115.47
La Matanza	32.09	115.94
La Tasajera	30.96	115.51
La Víbora	30.88	115.50
Laguna Juárez (Laguna Hanson)	32.04	115.91
Mesa El Roble	31.50	115.57
Misión San Pedro Mártir	30.79	115.47
Observatory	31.05	115.47
Ojos Negros	31.89	116.23
Paso San Matías	31.34	115.52
Picacho del Diablo	30.99	115.37
Rancho Nuevo	31.11	115.49
Rancho San Faustino	32.22	116.19
San Quintín	30.53	115.92
San Vicente	31.32	116.25
Santa Catarina plain	31.58	115.79
Santa Isabel	31.81	115.84
Santa Rosa	30.80	115.35
Santo Tomás	31.56	116.42
Sierra La Asamblea	29.35	114.07
Sierra Blanca	32.06	116.50
Sierra La Giganta	26.95	112.39
Sierra Juárez (SJZ)	32.5–31.5	116.25–115.55
SJZ "coast range"	32.4–31.7	116.9–116.4
SJZ "transverse range"	31.6–31.4	116.5–115.7
Sierra La Laguna	23.5	109.95
Sierra La Libertad	28.85	113.61
Sierra Peralta	31.61	116.23
Sierra San Francisco	27.50	113.01
Sierra San Pedro Mártir	31.25–30.4	115.6–115.4
Tecate	32.57	116.61
Tijuana	32.50	117.10
Vallecitos	31.00	115.48

Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
pp. 186–202

Valle El Pedregal	32.53	116.53
Valle Guadalupe	32.06	116.61
Valle Los Pinos	32.35	116.22
Valle Trinidad	31.39	115.75

TREE DISTRIBUTIONS IN NORTHERN BAJA CALIFORNIA

The following geographic ranges of Baja California tree species include the first detailed distributions of several tree species, and range expansions in several others. The maps presented here have greater precision than previous efforts (Minnich 1987; Minnich and Franco-Vizcaíno 1998), and are also available online in high resolution at the UCR Center for Conservation Biology website (*http://ccb.ucr.edu/*). Many species ranges given here represent their southern limits along the Pacific coast.

Closed-Cone Conifer Forest

Small discontinuous stands of closed cone conifer forests grow in extensive chaparral covering northern Baja California. Species in *Pinus* sect. *oocarpae* and *Cupressus forbesii* range within 30 km of the coast, while *P. coulteri* (*Pinus* sect. *sabinianae*) occurs inland in SJZ and SSPM.

Cupressus forbesii (3272.1 ha; Map 1).—In Baja California there are 1735 groves in the coastal mountains from the international boundary to San Quintín, a range of 280 km (cf. Little 1971). Stands are most abundant near Tecate, in the coastal range from Tijuana to Valle Guadalupe, E of Ensenada, and W of San Vicente. It is rare in the transverse range, but an interior outlier is found on a summit above Arroyo El Ciprés. In SSPM, Tecate cypress occurs in the western foothills and mesas, with the largest stands near Arroyo Santo Domingo and Cañon Nueva York. Beyond the southernmost collection of Moran at another Arroyo El Ciprés (30.38ºN, 115.63ºW, SDMNH-54829), we discovered colonies on hillsides 6 km ESE and 7 km SE (lat. 30.32ºN). Tecate cypress grows mostly on Paleozoic metasedimentary bedrock (Alisos formation) on north-facing slopes below 1100 m.

Cupressus guadalupensis (163.2 ha; Map 2).—The closely related *C. guadalupensis* is found on northern Guadalupe Island above 1000 m. The species lies largely above the fog zone of the coastal marine layer and experiences warm summers.

Pinus muricata (58.2 ha; Map 3).—Bishop pine occurs discontinuously along the coastal foothills for a span of 13 km near Eréndira, 14 km W of San Vicente. The largest groves occur in Cañon San Isidro and nearby Arroyo Hediondo. These populations grow below 400 m within 7 km of the coast line and are subject to wind-blown coastal low clouds, fog drip, and cool temperatures of the Pacific marine layer in summer. While these drainages comprise Paleozoic metasedimentary bedrock, bishop pine grows almost exclusively on small Eocene sandstone exposures. Stands are even aged from post-fire cohort regeneration, but trees on fire-resistant cliff outcrops are mixed-aged from continuous recruitment.

Pinus radiata D.Don (139.4 ha; Maps 2, 4).—The closely related *P. radiata* (Monterey pine) grows on foggy ridges between 300 and 600 m at the N end of Guadalupe Island (28.4 ha), as well as the N end and central "isthmus" of Cedros Island (111.0 ha). Stands are subject to high winds of the marine layer that contribute to fog drip that is vital for this species' survival, with a mean annual precipitation of 10–15 cm. Cedros Island populations were identified as *P. muricata* in Critchfield and Little (1966). Both populations are now recognized as *P. radiata*.

Pinus attenuata (475.3 ha; Map 5).—Critchfield and Little (1966) map the primary stand of *P. attenuata* (knobcone pine) on Cerro Miracielo N of Ensenada. Small populations also grow on Cerro Los Pinos, 30 km SE of Ensenada and on a ridge SW of Santo Tomás, 40 km S of Ensenada (Minnich 1987). We discovered a stand on Cerro El Golpe in the coast range N of Valle Guadalupe, the latter a range extension northward of 12 km N of Cerro Miracielo populations. Knobcone pine grows primarily on N-facing slopes below 1000 m. It is not known from the Sierra Juárez (cf. Wiggins 1980).

Pinus coulteri (738.3 ha; Map 6).—Six clusters of Coulter pine grow in SJZ and SSPM, mostly on bedrock outcrops with open cover of chaparral. In the coastal SJZ it grows on resistant granites of Sierra Blanca, with scattered trees descending adjoining Cañada de los Encinos toward Valle Guadalupe. This stand was described by Arrillaga during his explorations in 1796 (Minnich and Franco-Vizcaíno 1998). Farther inland, large populations grow on resistant granite bedrock slopes just W of Rancho San Faustino. Small groves and solitary trees extend 12 km N along this bedrock unit. A few trees were discovered at El Pinal, 10 km W of San Faustino. At

Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
pp. 186–202

Laguna Juárez (Laguna Hanson), Coulter pine grows with chaparral on granitic bedrock slopes NW of the lake. Outliers occur as far as 6.5 km W and 10.0 km N. Populations at Cañon El Rincón in the southern SJZ grow on volcanic caprock mesas (cf. Moran 1972). Remote Coulter pine forests at the far N and S ends of SSPM precluded their formal botanical discovery until 1987, although cones had long ago been collected by Felipe Meling (Minnich 1987). The northern SSPM population (lat. 31.14ºN; long. 115.49ºW), which spans the crest of the range for a distance of 8 km, is anomalous because it grows on smooth slopes of weathered metamorphic bedrock. Much of this population was fire-killed in 1989, and the post-fire cohort was too immature for mapping in Minnich et al. (2000). Recent Google Earth imagery records even-aged cohorts in virtually the same distribution as in aerial photographs before the 1989 fire (cf. Minnich 1986). The southern colony grows on granite bedrock slopes of Cerro “2040” and intermittently along an arroyo to the W for 7 km. We discovered a few trees on Cerro “2100”, 7 km to the N.

Riparian Forest (2563.4 ha; Map 7)

The two dominant species *Populus fremontii* and *Platanus racemosa* are mapped together because these hardwoods cannot be consistently differentiated from one another in a winter-deciduous state on Google Earth. Riparian forests grow along most watercourses <1200 m from the international border southward to Ensenada, then extend S in coastal foothills to San Vicente and E along the transverse range. Stands are rare in the interior valleys of Ojos Negros and the Santa Catarina plain, as well as the rain-shadowed southern SJZ volcanic tablelands. Impressive forests grow along Arroyos San Rafael and Santo Domingo for 20 to 40 km on the coastal side of SSPM (Minnich and Franco-Vizcaíno 1998). Riparian forests are replaced by blue fan palm (*Brahea armata* S.Watson) oases S of lat. 30.6ºN in southern SSPM, with palm oases continuing through the remainder of the peninsula (Minnich et al. 2011). Riparian forest is infrequent along the precipitous eastern escarpments of SJZ and SSPM where trees are washed out by flash floods, although *P. fremontii* is locally abundant along desert drainages at Arroyo El Cajon in central SSPM. Botanical collections show that *P. fremontii* is more widespread than sycamore and is the sole riparian tree in desert drainages. *Platanus racemosa* is most abundant along the coast and locally in the SJZ. Small groves were found in SSPM as far S as Cerro Chato. Massive cottonwood forests formerly covered the Colorado River delta before the area was cleared for agriculture (Minnich and Franco-Vizcaíno 1998).

Oak Woodlands

Oak woodlands are the primary forests at lower elevations of coastal northern Baja California. Oaks are also important understory of mixed conifer forest along the crest of the sierra.

Quercus agrifolia (15,853.8 ha; Map 8).—Coast live oak grows near stream courses and margins of basins eastward to the western flank of the Peninsular Ranges. Stands in the Laguna Mountains of San Diego County extend southward into SJZ but gradually decrease in abundance, the last stands occurring at Arroyo las Palomas. A coastal belt extends from Tijuana to Ensenada and Santo Tomás and eastward along the transverse range almost to Valle Trinidad. Coast live oak grows along the W face of SSPM to as far S as lat. 30.75ºN. An isolated colony was discovered in a desert drainage of the northern SSPM, 14 km from the nearest other stand (lat. 31.19ºN; long. 115.52ºW). Stands grow as high as 1900 m on the W face of the range. Although the southernmost major stands occur along Arroyo Santo Domingo, solitary trees occur as far S as Arroyo San Simón, 25 km farther S near San Quintín.

Quercus engelmannii (9.0 ha; Map 9).—According to Nixon (1997: 500), Engelmann oak (mesa oak) is closely related to, and possibly conspecific with, *Q. oblongifolia* Torr. (Mexican blue oak) of Arizona, New Mexico, and western Texas, as well as Sonora and Coahuilla, Mexico. In the Baja California peninsula, *Q. oblongifolia* occurs in the Sierra San Francisco, Sierra La Giganta, and the Sierra La Laguna. One botanical collection by John Tucker (SDNHM 95184) discusses the mixture of “intermediate oaks in the Sierra San Francisco.” Open woodlands of *Q. engelmannii* are widespread in the Peninsular Ranges of southern California, but mesa oak decreases in abundance toward the international boundary. In Baja California, vouchers have been collected from only a few small colonies at Valle El Pedregal 4 km S of Tecate. On Google Earth we found two colonies near Cerro San Javier, 13 km to the ESE. We also mapped several stands on a N-facing landslide deposit of a ridge near Bocana de Santo Tomás, a range extension of 100 km to the S. Cornelius Muller took a botanical collection of Engelmann oak at “Santo Tomas” in 1959 (SDNHM 121744). Bocana de Santo Tomás is moist, ideal

Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
pp. 186–202

habitat for the species due to orographic winter precipitation (mean 35 cm) and prevailing cool, marine air and low transpiration demand in summer.

Quercus peninsularis (7530.7 ha; Map 10).—Pacific Emory oak is closely related to *Q. emoryi* (Emory oak) of Arizona, New Mexico, western Texas, and northern Mexico southward to Durango and San Luis Potosí (Nixon 1997: 453 [*Q. emoryi*]). In Baja California, *Q. peninsularis* grows in Jeffrey pine forest and pinyon-juniper woodland in SJZ and SSPM. It seldom ventures into chaparral. Mapping of its distribution is greatly improved from Minnich (1987) due to higher quality imagery on Google Earth. The northern limit is near El Topo, 50 km S of the U.S.-Mexican border. It increases in abundance southward through SJZ with the largest populations between Arroyos El Tule and Las Palomas. The map is incomplete for the southern SJZ volcanic tablelands due to poor resolution of SPOT imagery on Google Earth, but *Q. peninsularis* was mapped on the aptly named Mesa El Roble. In SSPM, Pacific Emory oak grows almost exclusively on metamorphic rock exposures. The main stand extends from La Encantada and La Grulla meadows southward to Santa Rosa meadow and Arroyo Santa Eulalia. In northern SSPM, it grows on metamorphic exposures around the National Observatory and N of Cerro Venado Blanco. Pacific Emory Oak occurs in the chaparral sky islands of the Sierra La Asamblea and Sierra La Libertad in the Central Desert of Baja California.

Quercus chrysolepis (18,360.9 ha; Maps 11, 12).—Canyon live oak is a small-leaved shrubby ecotype compared to stands in California, but tall trees grow along washes and streams. In SJZ, numerous small colonies grow on fractured, N-facing granitic bedrock slopes and canyons in association with chaparral and pinyon woodlands. It is common on well drained slopes along the highest part of the plateau from Laguna Juárez (Laguna Hanson) to Santa Isabel. In the southern SJZ, it grows on talus and cliffs below volcanic caprock mesas. Rare colonies grow on the highest peaks of the coast range at Sierra Blanca, near Cerro San Antonio, Sierra Peralta, and Cerro León near El Alamo. In SSPM, canyon live oak is a widespread understory species in mixed conifer forest above 2100 m, mostly in open stands. It descends to 1800 m in canyons and N-facing slopes of the western and eastern escarpments, where it forms dense thickets. Canyon oak grows to an elevation of 2900 m near Picacho del Diablo. Remarkable populations occur in the Sierra La Asamblea in the Central Desert on a resistant pluton surface of bedrock and rock rubble, where trees apparently rely on bedrock runoff and secure reliable soil water in rock fractures. These stands are 175 km from the nearest population on Cerro Chato in southern SSPM.

Pinyon-Juniper Woodlands (122,573.0 ha; Map 13)

Pinyon-juniper woodland (*Pinus monophylla*, *P. quadrifolia*) is the most widespread tree assemblage in SJZ and SSPM, growing mostly above 1200 m. In SJZ, *P. monophylla* and *P. quadrifolia* form mixed stands on the McCain plateau southward to El Topo. In the remainder of SJZ and SSPM, these pinyons are geographically segregated (cf. Perry 1991; Lanner 1999). *Pinus quadrifolia* is dominant on coastal slopes in association with chamise and red shank chaparral, while desert-facing slopes are dominated by *P. monophylla* in association with open understory of desert chaparral (Minnich and Franco-Vizcaíno 1998; Minnich 2001). Local distributions reflect maturity states after stand-replacement fires. *Pinus monophylla* forms continuous old-growth forests, with most stands not having experienced fire for a century or longer. Mapped *P. quadrifolia* stands grow in chaparral patches of >50 years (Minnich and Chou 1997; Minnich et al. 2000), although continuous old-growth forests grow in the upper eastern escarpment of SSPM to as high as 2800 m. The southern limit of *P. quadrifolia* is near Cerro Chato. *Pinus monophylla* woodlands grow on the summit of the Sierra La Asamblea, 150 km to the SE in the central desert (Griffin and Critchfield 1972; Bullock et al. 2008). Our maps show that it grows on N-facing slopes of the main summit and on a resistant granite plutonic bedrock summit 5 km to the S, and on granitic slopes 7 km to the SSE. Searches of the Sierra La Libertad on Google Earth, the next range S of the Sierra La Asamblea, revealed no unequivocal evidence of pinyons.

Arizona Cypress Forest

The Arizona cypress complex includes *Cupressus arizonica* var. *glabra* (Sudw.) Little in Arizona and northwestern Mexico, *C. arizonica* var. *nevadensis* (Abrams) Little in the southern Sierra Nevada, *C. arizonica* var. *stephensonii* in San Diego County and southern SJZ, and *C. arizonica* var. *montana* in SSPM (Eckenwalder 1993: 406). In northern Baja California, numerous colonies of Arizona cypress extend over a distance of 150 km along the crest of

the southern SJZ and eastern escarpment of SSPM, with a gap of only 25 km at Paso San Matías.

Cupressus arizonica var. *stephensonii* (77.8 ha; Map 14).—In Baja California, "Cuyamaca" cypress occurs in the volcanic tablelands of the southern SJZ, 155 km SE of a small population on Kings Creek near Cuyamaca Peak in San Diego County, USA. The SJZ populations were first collected by Moran (1972) at 8 localites along Cañon el Rincón, but he speculated correctly that it also grew in other nearby arroyos. Low resolution SPOT imagery records widely scattered populations for a span of 43 km from Arroyo Las Palomas southward to a canyon near Cerro La Noche. Most stands lie near watercourses and apparently colonize in response to fluvial disturbance. Moran observed that shrubby stands in chaparral mesas N of El Rincón were burned in brushfires, with smaller bole dbh [diameter at breast height] and lower stature than stems along watercourses.

Cupressus arizonica var. *montana* (1124.6 ha; Map 15).—The first collections of *C. arizonica* var. *montana* were obtained above 2500 m on Picacho del Diablo and in washes of the nearby plateau, with apparent strong ecological segregation from *C. arizonica* var. *stephensonii* stands growing at lower elevations in SJZ. Subsequent collections and new maps from Google Earth have greatly enlarged the distribution and ecological range of *C. arizonica* var. *montana*. In 1987, it was collected on the E escarpment at Rancho Nuevo near Cerro Venado Blanco, 10 km N of Picacho del Diablo (UCR-51556). Large stands were seen on slopes to the E. Digital Globe imagery taken in 2007 shows the distinctive turquoise foliage of the species (Table 1). We have extended the range of mountain cypress along the eastern escarpment northward from Picacho del Diablo to Cerro Venado Blanco and disjunctly to Cerro San Matías. We have also extended the range southward from Picacho del Diablo along the eastern escarpment to points opposite La Encantada, Santa Rosa, Santa Eulalia, Cerro Chato, and Arroyo El Berrendo in far southern SSPM. The mapped N–S range of *C. arizonica* in SSPM is 90 km, but the tree is rare S of La Encantada. Mountain cypress is absent from the SSPM plateau except along stream courses from Cerro Botella Azul to the S end of La Encantada. Moran collected specimens from one tree along an arroyo at La Víbora. It is widespread on granite substrate, but occurs locally on precipitous metamorphic exposures on the eastern escarpment S of La Encantada, as well as on volcanics in southern SSPM. The elevation of stands in the far northern and southern ends of its range in SSPM (1500 m) overlaps with *C. arizonica* var. *stephensonii* in SJZ. Several populations in the N exhibit cohort regeneration in dense chaparral burned in 1975, similar to that observed in cypress by Moran in the southern SJZ, as well as the population on Kings Creek in San Diego County (Minnich and Everett 2001; Goforth 2009).

These new maps of *C. arizonica* var. *stephensonii* and *C. arizonica* var. *montana* document convergence in elevation and habitat, with both varieties jointly extending a distance of 150 km along the Baja California Peninsular Range and a gap of only 30 km at Paso San Matías. These taxa should be reviewed to see whether the alleged differences are consistent, especially populations close to the gap at Paso San Matías (elevation 900 m), which is unsuitable habitat for the species. Material has not been collected except in limited areas near Arroyo El Rincón and Picacho del Diablo.

Mixed Conifer Forest

Higher elevations of SJZ and SSPM are covered with open mixed-conifer forests 25–40 m tall, dominated by mature trees >60 cm dbh with crown bases 5–10 m above ground. Large surface fires run freely through these forests at intervals of 2–3 events per century (Minnich et al. 2000), in contrast with dense "fuel-ladder" forests that have developed with a century of fire suppression policies in nearby California, and ponderosa pine forest in the southwestern USA.

Pinus jeffreyi (48,391.6 ha; Map 16).—Jeffrey pine is the dominant tree of mixed conifer forest in the SJZ and SSPM. In SJZ, patchy monotypic forests grow in basins from Valle Los Pinos to Cañon El Rincón in the southern volcanic tablelands, with continuous stands from Laguna Juárez to Santa Isabel. Small colonies occur on Cerro San Matías (2150 m) in far northern SSPM, including solitary trees on a summit 2 km N, and small groves in nearby basins to the SW. In SSPM proper, Jeffrey pine forms a continuous belt above 2100 m from Cerro Venado Blanco to Vallecitos, La Grulla, and La Encantada. To the S, Jeffrey pine is confined to basin floors, the transition occurring at a contact between granitic bedrock to the N and metamorphic exposures to the S. Jeffrey pine is absent to rare in mixed conifer forests on the upper eastern escarpment and the cliffs of Picacho del Diablo, but it grows near creeks in metamorphic zones N of the observatory. Plateau stands extend as

far S as Arroyo Santa Eulalia (lat. 30.62ºN) where Google Earth imagery records only a few trees along watercourses beyond the southernmost collection by Moran (SDNHM-54804).

Abies concolor (16,211.8 ha; Map 17).—White fir is found in SSPM above 2200 m from Cerro Venado Blanco to Vallecitos and watersheds N and E of La Grulla and La Encantada. It is the dominant species on N-facing slopes on Corona Arriba, the upper eastern escarpment, and bedrock slopes of Cerro Venado Blanco. White fir is infrequent in metamorphic units, including the upper catchments of Río San Rafael, but is locally abundant on granite exposures embedded within this metamorphic unit. No trees were found S of La Grulla and La Encantada (cf. Wiggins 1944).

Pinus lambertiana (1689.7 ha; Map 18).—Sugar pine has virtually the same range as *Abies concolor*, but populations are discontinuously restricted to steep, mostly N-facing exposures on granitic bedrock. It is most abundant on Corona Arriba, Cerro Venado Blanco, Cerro Botella Azul, and upper N-facing catchments of the eastern escarpment. *Pinus lambertiana* is absent from metamorphic slopes except on the eastern escarpment. It forms locally monotypic stands rooted into N-facing granitic bedrock cliff fractures of the escarpment. Sugar pine extends farther S than white fir, with isolated colonies extending to the S side of La Grulla and La Encantada on resistant granite bedrock slopes. Two trees were found on an isolated granitic exposure just N of Santa Rosa, and 9 km S of the nearest other stand.

Calocedrus decurrens (150.8 ha; Maps 19, 20).—Incense cedar is the only other mixed-conifer tree species growing in Jeffrey pine forest of SJZ. We report range extensions, as botanical collections of Moran report it only from La Matanza and Arroyo El Tule. Incense cedar also occurs along watercourses draining Laguna Juárez and locally between the lake and Arroyo El Tule. In SSPM, *Calocedrus decurrens* occurs along stream courses on the plateau, as well as the western and eastern escarpments. It is an occasional member of mixed conifer forest away from stream courses from Corona Arriba to La Tasajera and common at the N end of Cerro Venado Blanco. The stand near Misión San Pedro Mártir is the southern limit of the species. A report of incense cedar in upper Arroyo El Cajon near Santa Rosa by Wiggins (1944) cannot be confirmed.

Populus tremuloides (327.8 ha; Map 21).—Quaking aspen occurs in SSPM above 2300 m, mostly near streams and meadows from Cerro Venado Blanco to Vallecitos. Large stands grow on granitic bedrock slopes of Cerro Venado Blanco, the National Observatory, Cerro Botella Azul, and E of La Encantada. Other populations grow on the southwestern and eastern flanks of Vallecitos meadow, and along watercourses E of Corona Arriba. Dense thickets grow in mixed conifer forests recently denuded in stand replacement burns on Cerro Botella Azul. A single colony grows at an outlet of Santa Rosa Meadow at 2030 m, 15 km from the nearest other stand and the southern limit of the species along the Pacific coast. The SSPM stands are 360 km from two colonies in the San Bernardino Mountains, and 600 km from stands in the southern Sierra Nevada.

Subalpine Forest

In the Transverse and Peninsular Ranges of southern California, subalpine forests of *Pinus contorta* and *P. flexilis* E.James grow on the highest peaks above 2400–2600 m. The next forests S are *P. contorta* stands in SSPM, ca. 290 km from the nearest population in the San Jacinto Mountains.

Pinus contorta (1315.2 ha; Map 22).—The SSPM lodgepole pine forests are most extensive at the low end of its elevational range. Only scattered groves occur on the highest peaks above 2600 m on bedrock exposures and talus, including the eastern ridge from the observatory and the summits of Picacho del Diablo. It is locally common but never dominant on Cerro Botella Azul, the highest peak of the plateau (2960 m). Lodgepole pine is most extensive near meadows at 2400 m at Vallecitos and La Tasajera and along watercourses near Corona Arriba. These lower sites experience strong ground inversions at night (temperatures as low as -30ºC; Alvarez 1981) and experience poor water drainage associated with frozen soils as well as extensive ponding or flooding behind snowbanks in spring snowmelt. These are the only *P. contorta* forests in Mexico.

CONCLUSION

Google Earth is a breakthrough in the development of regional vegetation science as an intellectual pursuit. Maps produced at different scales on this software can be correlated with one another. Regional change can be quantified from local scales, and variation in local patterns can be quantified with

respect to the regional pattern. This breakthrough is timely in view of recent concern for monitoring future biotic change in response to global climate change, but predictions can be rigorously constrained by empirical data. The tradition and legacy of remote sensing has been testing for map quality. Of course, field work is necessary to make sense of imagery by associating species with diagnostic criteria (Table 1). But testing protocols for map accuracy does not add to the advancement of the science. A better approach is to ask the traditional scientific question: how do we improve upon previous work? Coupling high-resolution maps to the collective work of generations of scientists will refine and improve vegetation maps. This has been the tradition of geology since the 19th century, which resulted in the eventual agreement on the geologic time scale through local mapping and regional correlation of rock units. Using Google Earth, high precision maps can be made by digitizing directly on imagery, and the seamless scaling allows for regional characterization of the vegetation by different workers. Moreover, future investigators will not be obliged to use previous classification systems because they will have access to the raw data in historical Google Earth imagery, as well as historical sources of aerial photography.

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MAPS

Maps 1–22. Tree distributions in northern Baja California. Maps are grouped four to a plate. [All maps N to top].

Maps 1–4.—1. Distribution of *Cupressus forbesii*. Arrow locates the southernmost stands E of San Quintín.—2. Distribution of *Cupressus guadalupensis* and *Pinus radiata* on Guadalupe Island. Contours indicate the elevation range of summer coastal fog interfacing land, mostly 300–600 m; *C. guadalupensis* grows above the fog zone.—3. Distribution of *Pinus muricata*.—4. Distribution of *Pinus radiata* on Cedros Island. Contours indicate the elevation range of summer coastal fog interfacing land, mostly 300–600 m.

Maps 5–8.—5. Distribution of *Pinus attenuata*. Arrows locate new colonies on Cerro El Golpe (top) and on a ridge near Santo Tomás (bottom).—6. Distribution of *Pinus coulteri*. Arrows locate range extensions near Rancho San Faustino (top) in the Sierra Juárez, and on a summit north of known populations on Cerro "2040" in the southern Sierra San Pedro Mártir (bottom).—7. Distribution of *Populus fremontii* and *Platanus racemosa*. Rare *P. fremontii* stands S of latitude 30°N are not shown in the inset map.—8. Distribution of *Quercus agrifolia*. Arrows locate a disjunct stand on the eastern escarpment of the northern Sierra San Pedro Mártir (right middle), and solitary trees S of known stands along Arroyo Santo Domingo (bottom).

Maps 9–12.—9. Distribution of *Quercus engelmannii*. Arrows locate stands near Tecate (left top) and Cerro San Javier (right top), and along a ridge E of Bocana de Santo Tomás, S of Ensenada (bottom).—10. Distribution of *Quercus peninsularis*. Dots in the inset map depict populations in the Sierras La Asamblea (N) and La Libertad (S) in the central desert.—11. Distribution of *Quercus chrysolepis* in the Sierra Juárez. Arrows locate isolated colonies on summits of the coast range.—12. Distribution of *Quercus chrysolepis* in the Sierra San Pedro Mártir. Inset map shows *Q. chrysolepis* stands in the Sierra La Asamblea of the central desert.

Maps 13–16.—13. Distribution of *Pinus quadrifolia* and *P. monophylla*. White line is a dominance boundary between these pinyon species, with *P. quadrifolia* forming monotypic pinyon forest in most places along the western face of the Peninsular Range. *Pinus monophylla* is largely restricted to the eastern escarpment.—14. Distribution of *Cupressus arizonica* var. *stephensonii* in the southern Sierra Juárez.—15. Distribution of *Cupressus arizonica* var. *montana* in the Sierra San Pedro Mártir.—16. Distribution of *Pinus jeffreyi*.

Maps 17–20.—17. Distribution of *Abies concolor*.—18. Distribution of *Pinus lambertiana*. Arrow locates an isolated colony on the N side of Santa Rosa meadow.—19. Distribution of *Calocedrus decurrens* in the Sierra Juárez. Arrows depict new populations between known stands at La Matanza and Arroyo El Tule.—20. Distribution of *Calocedrus decurrens* in the Sierra San Pedro Mártir. Arrow locates southernmost population of the species near Misión San Pedro Mártir.

Maps 20–21.—21. Distribution of *Populus tremuloides*. Arrow locates a disjunct population near Santa Rosa meadow.—22. Distribution of *Pinus contorta*.

Minnich et al.: Tree Species Distributions
Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
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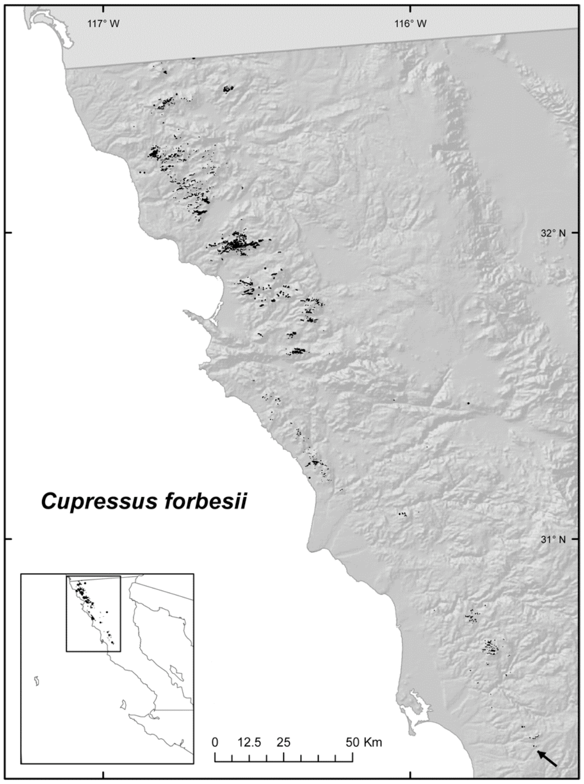

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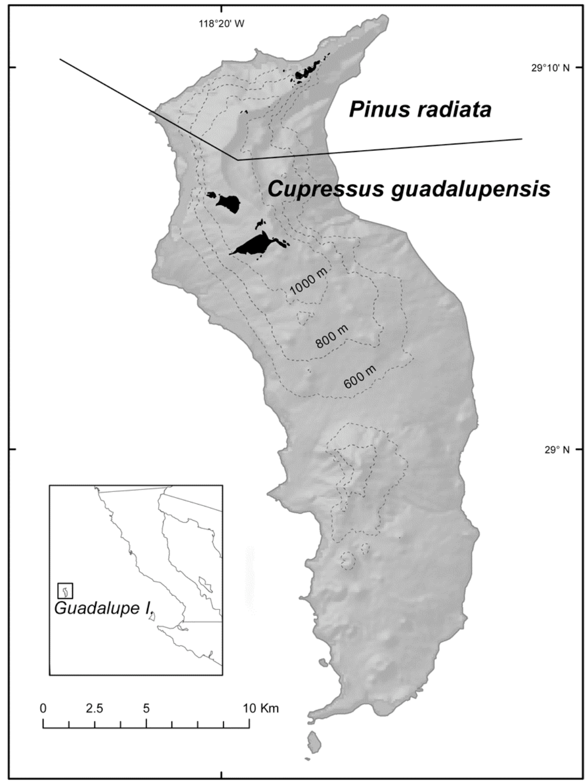

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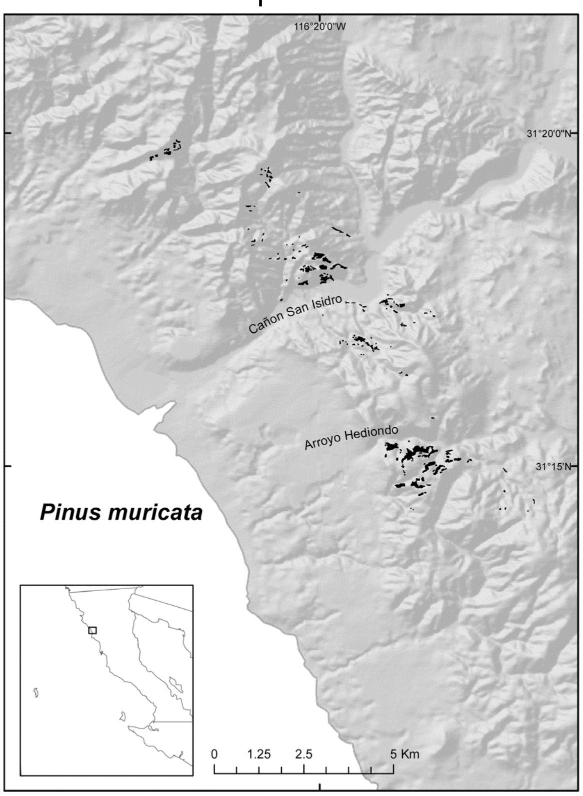

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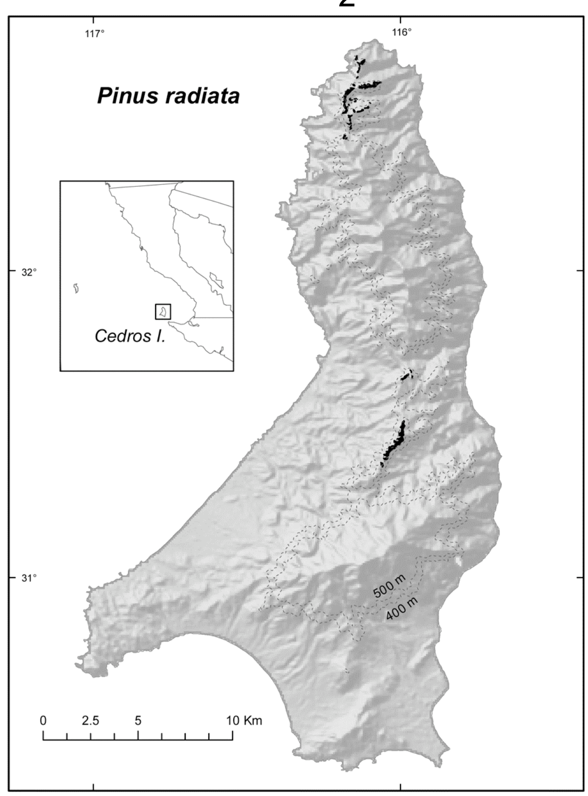

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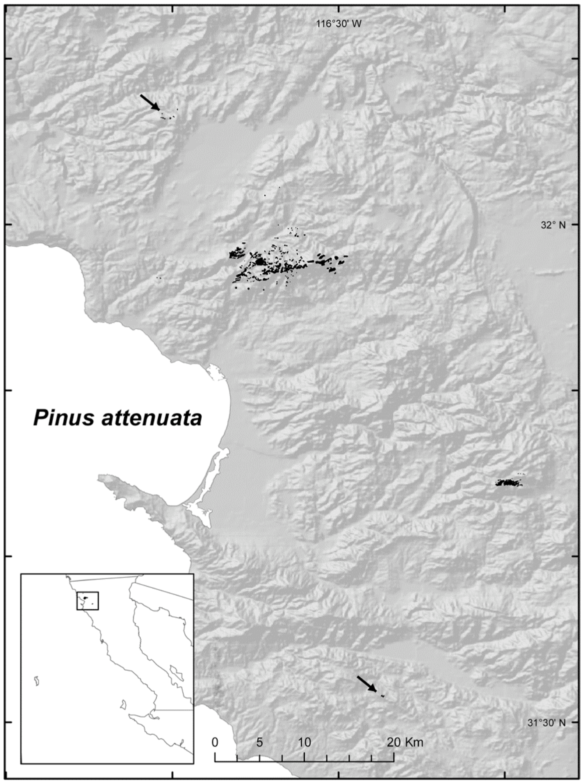
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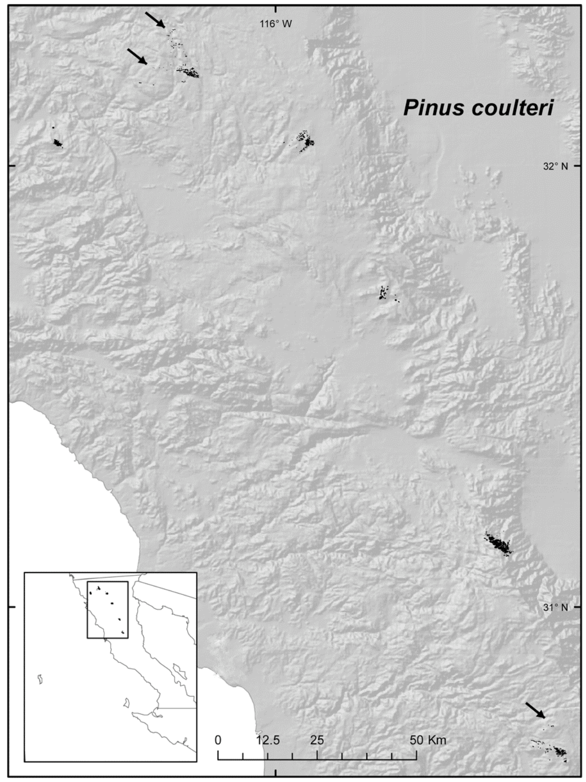
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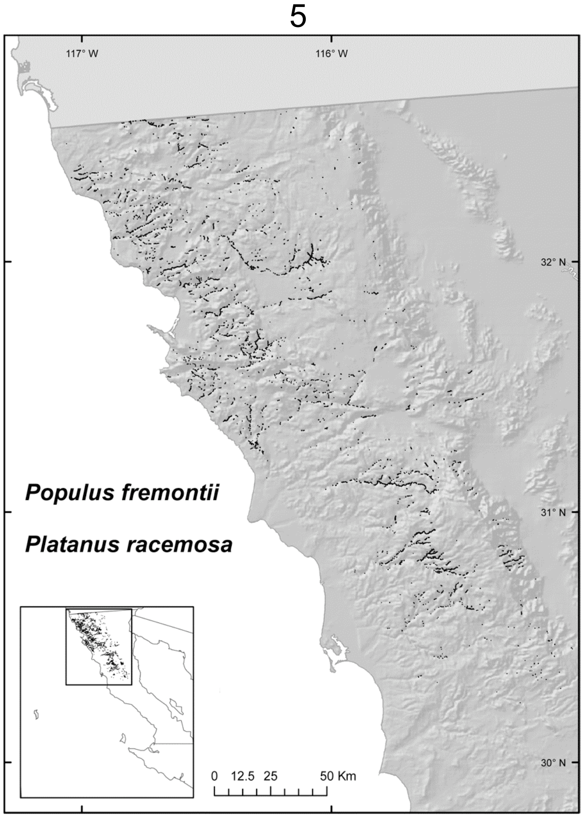
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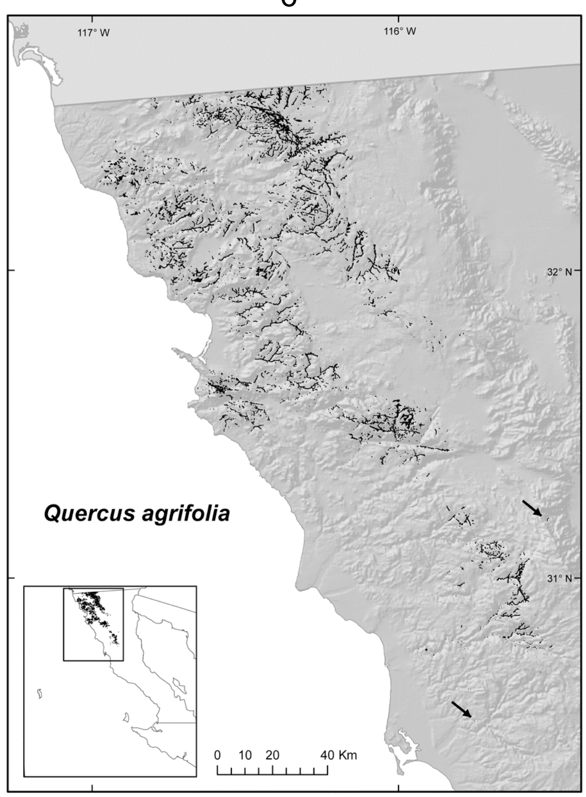
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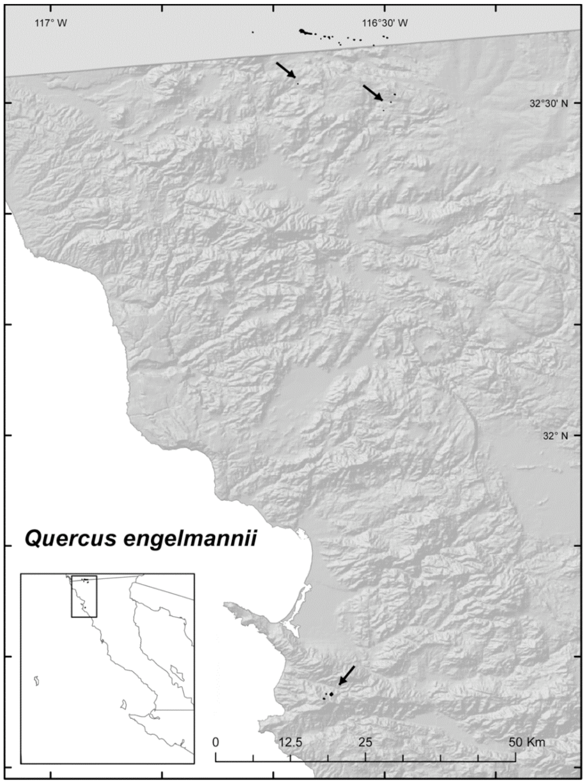
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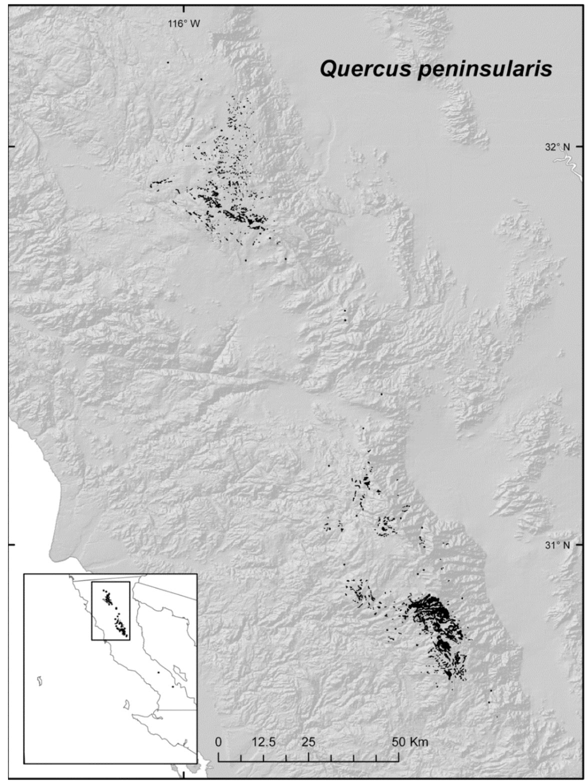
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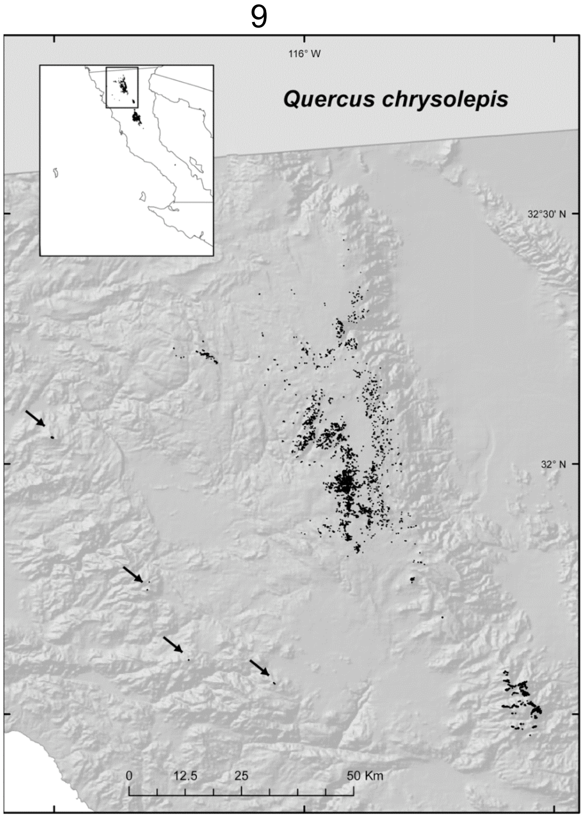
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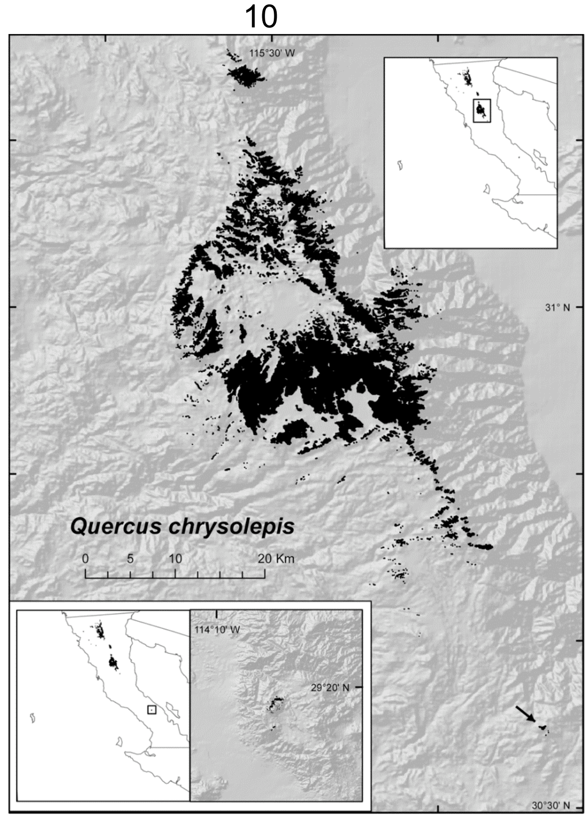
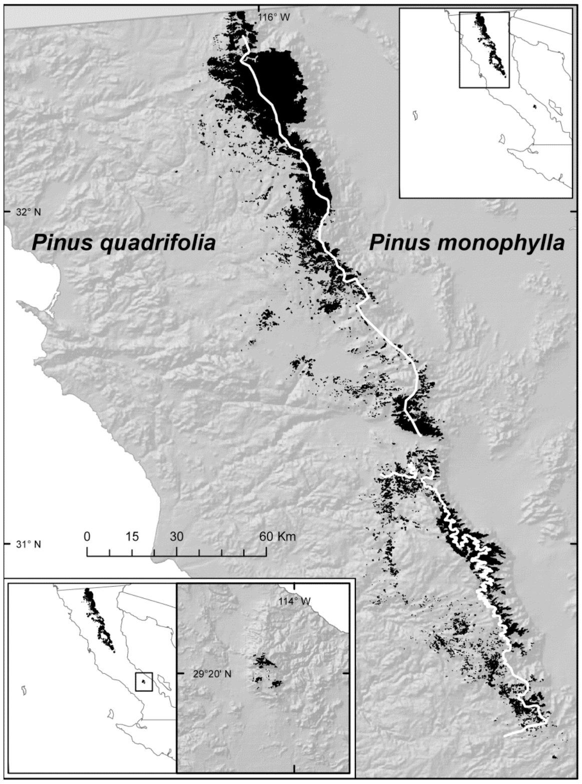
0
12.5
25
50 Km

11

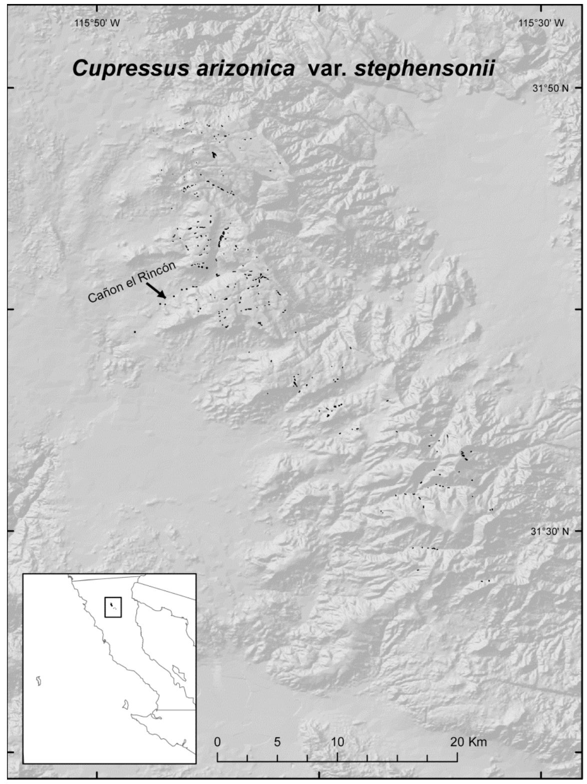

115°30' W
31° N
Quercus chrysolepis
0
5
10
20 Km
114°10' W
29°20' N
30°30' N

12

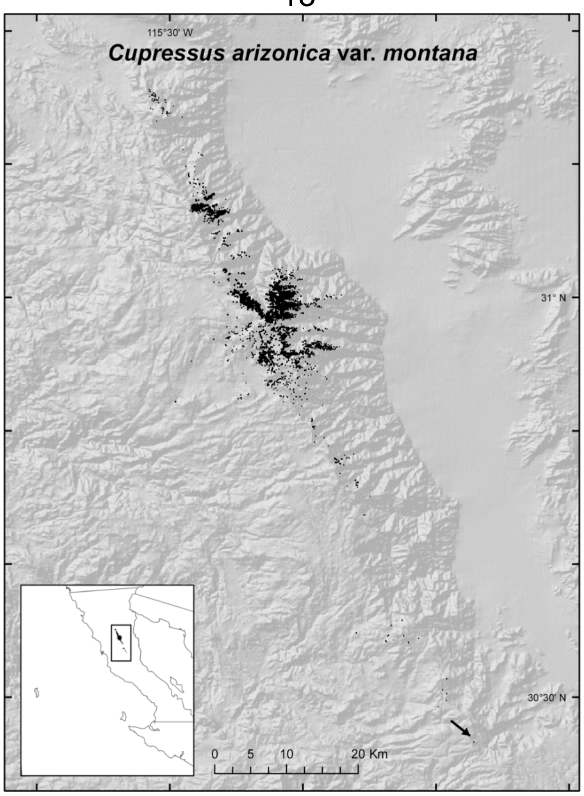
Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
pp. 186–202



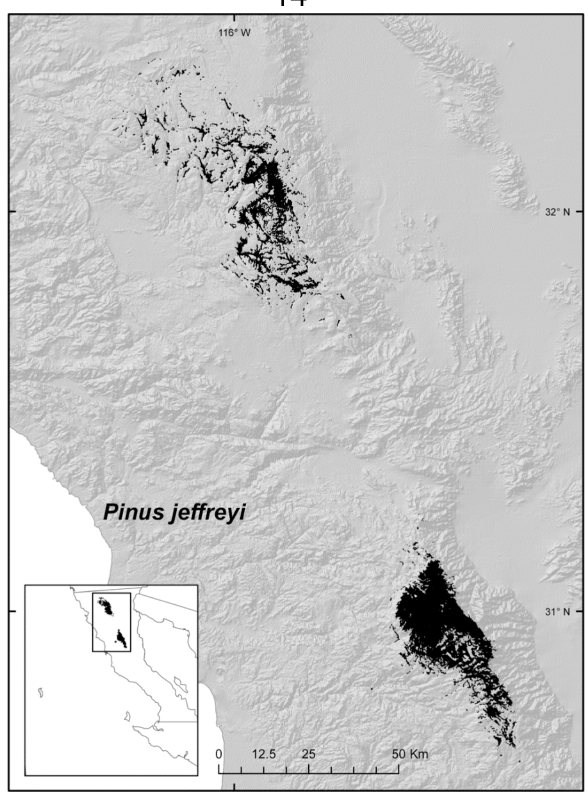
13



14

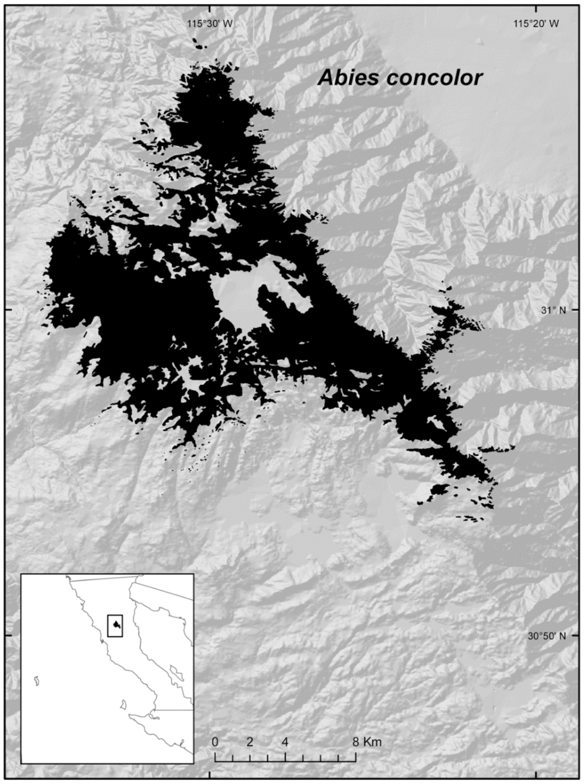


15

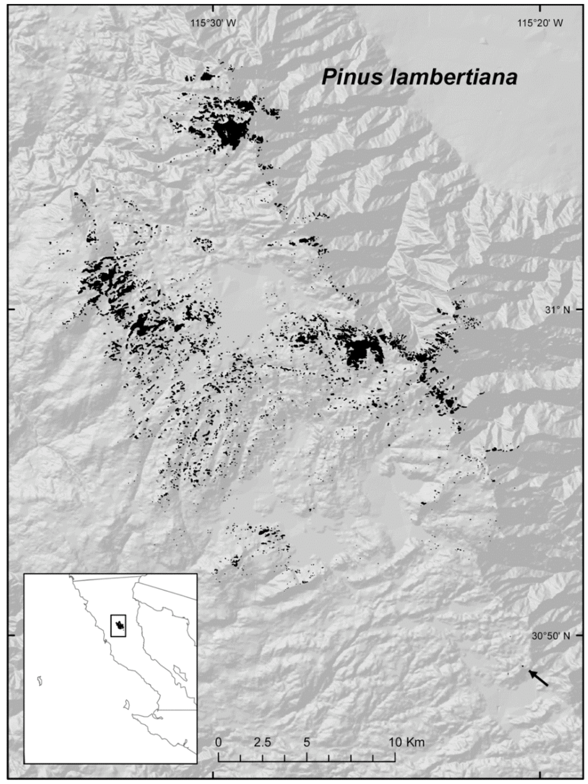


16

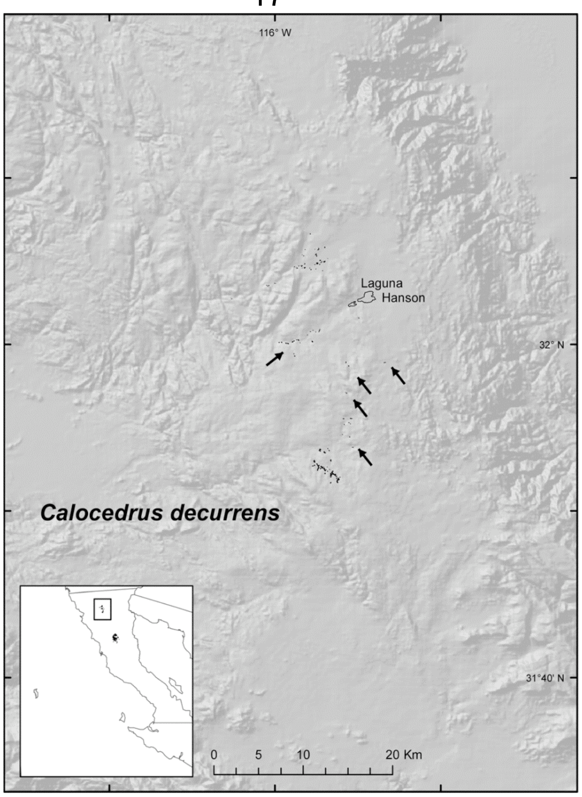
Proceedings of the CNPS Conservation Conference, 17–19 Jan 2009
pp. 186–202



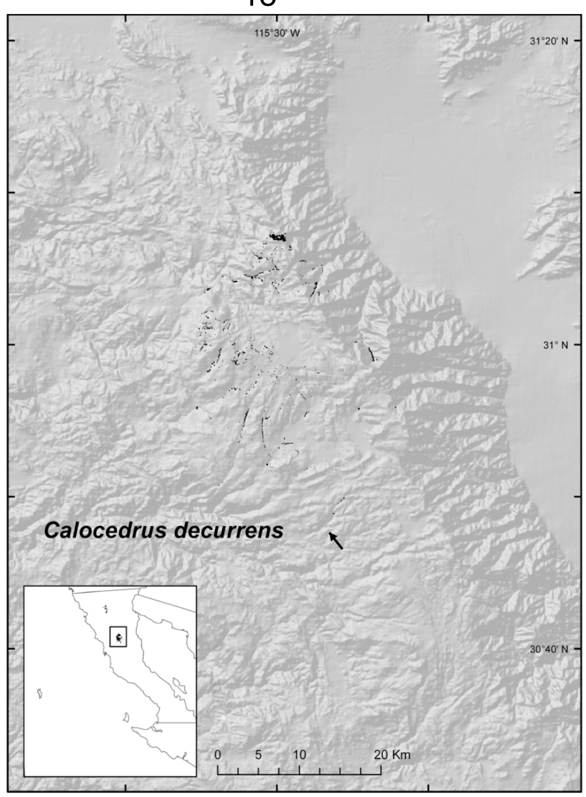
17



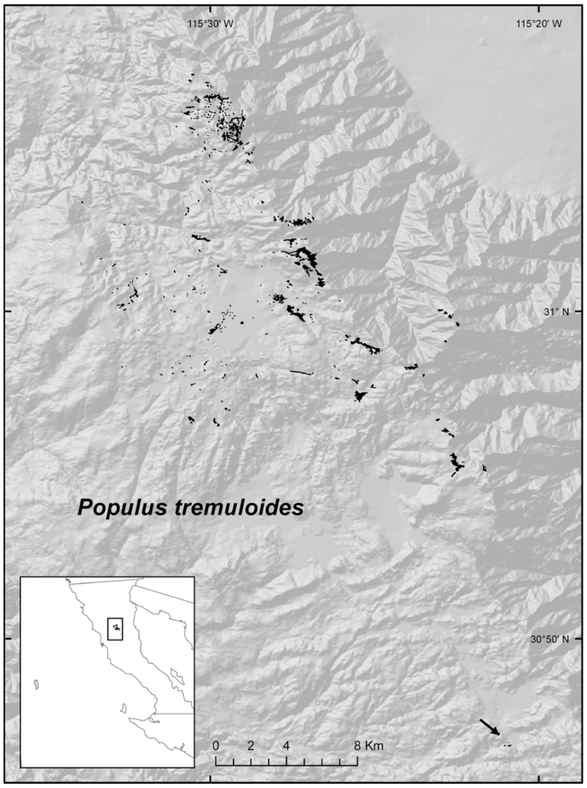
18



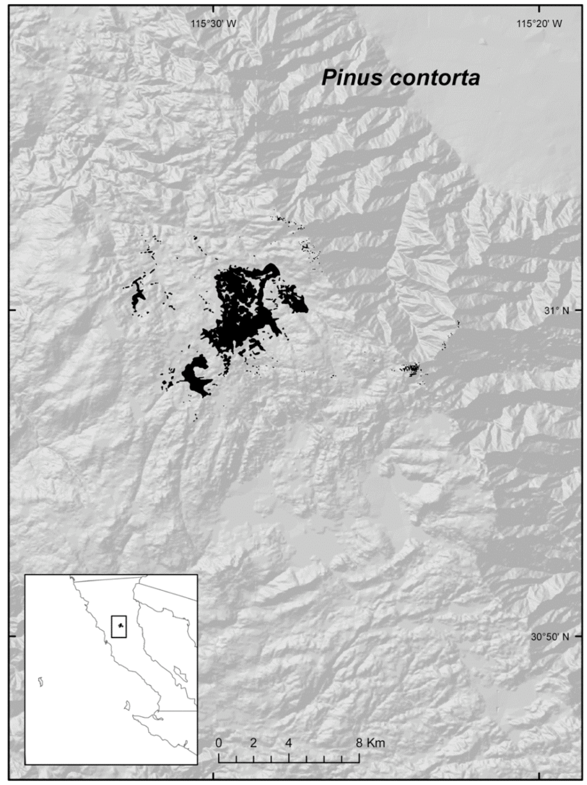
19



20


115°30' W
115°20' W
31° N
30°50' N
Populus tremuloides
0 2 4 8 Km

21


115°30' W
115°20' W
Pinus contorta
31° N
30°50' N
0 2 4 8 Km

22